CHAPTER 4

MICROSCOPIC LIKE TRIP ANALYSIS

This chapter furthers the analysis of similar trips by comparing the usage of ICC (Intelligent Cruise Control) to CCC (Conventional Cruise Control) at the micro-level. The results presented in this chapter are based upon deci-second data extracted from similar trips. The purpose of the data extraction was to isolate the effects of a particular driving mode. A description of the process used to extract data for a high speed arterial facility and a freeway facility immediately follows this chapter introduction.

The second section of this chapter is an analysis of the day-to-day variations in traffic behavior. This was performed with respect to speed, acceleration and headway differences between ICC, CCC and manual driving modes.

The third section is a comparison of car-following behavior. Once again, the comparison is based upon the data extracted for the two road classes and on the three driving modes: ICC, CCC and manual. This section is divided into four separate analyses. The first analysis was to determine the most probable speed, acceleration and headway for each mode. The second was to determine the probability of using either cruise control mode with respect to driving speed. The third and fourth were comparisons between speed-headway relationships and speed-flow-density relationships.

The final section includes conclusions and recommendations based on the micro-level analysis.
4.1 Extraction of Data

As indicated in the introduction to this chapter, the purpose of the traffic data analysis was to compare ICC to CCC at a micro-level. In order to achieve this goal, the effects of a particular mode were isolated. This section describes the isolation of mode effects, driver selection and the data extraction procedure. First, the factors considered in the data extraction process are described.

4.1.1 Isolation of Mode Effects

As indicated, it was desired to remove as many outside variables as possible in order to isolate a particular driving mode. With consideration of trip origin, trip destination, time of day, vehicle driver, and road class the end result was to extract data that corresponded to a particular road. The following paragraphs describe the relationship of these factors to the extraction of deci-second trip data.

As an initial filter, only similar trips were considered. The purpose of this was to ensure similar start and end locations as well as a similar time of day start time. In addition, the effects of varying drivers was removed since similar trip sets were prepared for each driver and not across drivers. The spatial location of origin and destination tolerance was 0.1 km and the trip start time difference tolerance was 0.25 hour.

In order to determine a particular roadway’s data, the road class was plotted against cumulative distance. The assumption was that if two or more trips of approximately equal length start in similar areas and end in similar areas as well as follow similar road class patterns, then the common road class portion across all similar trips being analyzed actually represented one particular road.
The two previous paragraphs described the characteristics of the data required for analysis. The remainder of this section describes the extraction of data from the trip database files.

### 4.1.2 Driver Selection

It was desired that the quantity of data extracted be as much data as possible given the restriction that data came from similar trips. The selection of a driver for data extraction was based upon several factors: the number of similar trips the driver performed, the number of like trip sets, and the number of ICC and non-ICC trips performed in each like trip set.

Driver 43 was initially chosen for analysis due to the large number of similar trips (36) and the mix of trips performed in week one and week two. Similar trip set one contained five trips performed in week one without ICC and five trips in week two with ICC usage. As shown later in this section the only facility used in this like trip set for all three driving modes was a high speed arterial. The remaining similar trip sets for driver 43 each showed the same facility type being used by all three driving modes. Therefore, the only useful facility data obtained from driver 43 related to a high speed arterial.

To better understand the effects of a particular driving mode, it was considered beneficial to compare data from different facility types. Since cruise control use is often associated with freeway driving, a second driver was found who used a freeway facility. From the remaining driver data available, driver 53 was chosen since similar trips used a freeway facility. The best similar trip set (number 5) contained two trips for each week.
4.1.3 Individual Road Class Charts

Once the selection of the driver and similar trip set number was complete road class versus cumulative distance plots were created for each trip to visualize the driving modes used for a given road class. Four of these trip plots are shown in the following figures. The next two figures represent trip one from week one and trip three from week two for driver 43.

![Figure 4-1 Road Class Determination for Week 1 Trip (Driver 43)](image1)

![Figure 4-2 Road Class Determination for Week 2 Trip (Driver 43)](image2)
From the above two figures it is seen that manual, CCC and ICC driving modes have only one common type of road class: number two. Therefore, in order to compare the three different modes with consideration to road class, only road class two was used.

The next two figures show the first trips made in weeks one and two for driver 53.

Figure 4-3 Road Class Determination for Week 1 Trip (Driver 53)

Figure 4-4 Road Class Determination for Week 2 Trip (Driver 53)
Similar to driver 43, driver 53 used all three modes on one facility type only. It is this facility, facility one, which was used for data comparison. Once the common facility was selected, data was then extracted such that for the cumulative distance selected all trips used this particular facility only. This extraction process is described next.

4.1.4 Composite Road Class Charts

The graphs presented in this section are intended as a visualization of the data extraction procedure. These charts compare the individual trips of a similar trip set based on road class. Trips performed by driver 43 are separated by week while all trips performed by driver 53 are shown on one graph.

Recall that the trips illustrated above are similar trips. This means that all trips started within 0.1 km and ended within 0.1 km of each other. Also note that all trip lengths were similar and road classes used for a given cumulative distance were also similar. Figure 4-5, therefore, suggests that the routes did not really change for these five similar trips. The common facility as previously determined was facility two, which
was classified as a high speed arterial. There were common portions, however, for other facilities. For example, facility five was used in all five trips near the start of each trip. Cruise control was not used on this facility, however, so analysis was not performed. The next figure shows the five trips performed by driver 43 in week two for similar trip set one.

![Graph showing cumulative distance and road class for Week 2 trips](image)

**Figure 4-6 Road Class Determination for all Week 2 Trips (Driver 43)**

Once again, the similar road class patterns and trip distances indicate that routes did not really change between trips. By the same reasoning it can be said that the routes did not change between weeks as well. The data was extracted based on the cumulative distances for each trip in this set. The cumulative distance at which each trip first used the high speed arterial and the cumulative distance at which each trip left the high speed arterial were found. Then the maximum start distance and minimum end distance were found looking at all trips. All data between these two points was then extracted for each trip in the set. Note that road class 10 was used for a small distance in one of the trips performed in week two. The cumulative distance values extracted from all trips exclude this portion. The next figure shows all trips performed by driver 53 in similar trip set five.
Similar to the situation for driver 43, the above figure indicates that routes were similar for all trips performed by driver 53. The trip lengths for driver 53, however, were much longer than the lengths for driver 43. The common facility used by driver 53 was facility one, which is a freeway. This is the only facility that saw the usage of all three driving modes: ICC, CCC and manual. The data extraction procedure was identical to the procedure used for driver 43. The maximum value of cumulative distance for initial road class one use was found and the minimum of the last use of road class one was also found. The values of cumulative distance between these two values were extracted for all trips.

The process used to extract data for a high speed arterial facility and freeway facility has been described in this section. The stage is now set for day-to-day variation analysis and analysis of car-following behavior.
4.2 Day to Day Variations in Traffic Behavior

As explained in the previous section, deci-second data has been extracted for both a high speed arterial facility and a freeway facility. Trip comparisons were made based on speed, acceleration and headway. Initial visual comparisons were made for several trip pairs for each road class followed by the calculation of correlation values. This section includes the initial trip comparisons, the correlation calculation process and a discussion of the correlation results.

4.2.1 Trip Comparisons

The purpose of the graphs shown below is to illustrate that differences between trips existed along the entire length of the trip, including the extracted portion that is further analyzed in the following sections. Graph pairs showing speed, acceleration and headway for driver 43 and driver 53 are now shown.

![Figure 4-8 Speed versus Cumulative Distance (Driver 43, Trip 1-2)](image)

Figure 4-8 Speed versus Cumulative Distance (Driver 43, Trip 1-2)
The above graph illustrates the speed versus cumulative distance relationship for the second trip performed by driver 43 during the first week. The next figure is a plot of speed versus cumulative distance for the third trip performed in the first week by driver 43.

Figure 4-9 Speed versus Cumulative Distance (Driver 43, Trip 1-3)

There are obviously many differences between the speeds for these two trips. For example, at a cumulative distance of 3000 m the speed in trip 2 was approximately 90 km/h while at the same location in trip 3, the speed was less than 80 km/h.

The next charts illustrate that differences also existed for acceleration between two similar trips performed by driver 43. The first graph of the pair represents trip number one of week two and the second shows trip three of the same week.
Figure 4-10 Acceleration versus Cumulative Distance (Driver 43, Trip 2-1)

Figure 4-11 Acceleration versus Cumulative Distance (Driver 43, Trip 2-3)
It is easily noted that differences exist between the above two graphs. The first graph of the two indicates an acceleration of approximately zero for a portion of the trip near the 4000 m cumulative distance mark. At this same cumulative distance for the trip three chart, the acceleration was not constant.

The next pair of graphs indicate differences in the range versus cumulative distance for two trips performed by driver 43 in week two of the field operational test.

Figure 4-12 Range versus Cumulative Distance (Driver 43, Trip 2-3)
Each pair of graphs shown for driver 43 above indicates that day to day variation existed in speed, acceleration and range. Similar to the charts just shown, the following pairs of charts illustrate that differences existed between trips performed by driver 53 with respect to speed, acceleration and headway. Speed versus cumulative distance plots for trips one and two of week two for driver 53 are shown in Figure 4-14 and Figure 4-15 respectively.
The two graphs shown above indicate differences in speed between the two trips. For example, the ICC portion at a cumulative distance of 10,000 m had a fairly constant speed in the second trip just above 100 km/h while in the first trip the speed decreased
to 80 km/h for that same portion of the trip. A pair of trips created from week one acceleration data are shown next.

Figure 4-16 Acceleration versus Cumulative Distance (Driver 53, Trip 1-1)

Figure 4-17 Acceleration versus Cumulative Distance (Driver 53, Trip 1-2)
As with the previous graph pairs, there were differences between the two acceleration graphs for driver 53.

![Graph 1](image1.png)

**Figure 4- 18 Headway versus Cumulative Distance (Driver 53, Trip 2-1)**

![Graph 2](image2.png)

**Figure 4- 19 Headway versus Cumulative Distance (Driver 53, Trip 2-2)**
This final trip pair comparison indicates that there were differences in headway values for driver 53. Note that these plots are in terms of headway while the driver 43 plots were shown a range plots. The length of a vehicle was considered to be 8 m in all range to headway calculations.

### 4.2.2 The Correlation Procedure

The graphs shown in the previous section indicate that differences existed in headway, speed and acceleration for two similar trips performed on different days. The purpose is now to perform trip pair comparisons for each driver to determine the correlation between the headway, speed and acceleration for a pair of similar trips performed on different days.

Three trip pairs were selected for both driver 43 and driver 53 for comparison. Trip selection was based upon the week that the trip was performed. The first pair consisted of two trips performed during week one of the field operational test. The second pair consisted of two week two trips. The third and final pair was a comparison of one trip performed in week one and one trip performed in week two.

Trips were compared on a cumulative distance basis. As previously indicated, data was extracted for a particular facility. Even though the cumulative distances fell into a particular range the number of data points recorded for each trip within this range were not equal. A direct comparison of headway, speed or acceleration based upon each cumulative distance point recorded would be difficult. Therefore, the data for each trip were averaged over a specific cumulative distance interval. The bin size chosen for driver 43 was 250 m while the interval chosen for driver 53 was 1000 m. This selection was based upon the total cumulative distance covered (less than 10 km for driver 43 and closer to 50 km for driver 53). In order to maintain as much of the data as possible, mode was not considered in these comparisons. If mode were to be included, matching of common mode portions would decrease the amount of data that
could be compared. Data associated with range equal to zero points were removed because at large range distances it was recorded as zero. Including these points would have decreased the calculated averages whereas the opposite would represent the true average values. Once bin averages were calculated for each trip, correlation values were determined (using Microsoft Excel 97 data analysis tools) based upon these average points. Calculation of correlation values used the following (Microsoft Excel 97):

\[
\rho_{X,Y} = \frac{\text{cov}(X,Y)}{\sigma_X \cdot \sigma_Y}
\]

Where \( \sigma_X^2 = \frac{1}{n} \sum (X_i - \mu_X)^2 \), and \( \sigma_Y^2 = \frac{1}{n} \sum (Y_i - \mu_Y)^2 \).

If two trips are identical in all aspects then the calculated correlation value should equal one. In addition, if the two trips have no similarity whatsoever then the calculated correlation would be zero. Negative correlation values are an indication of variation in this situation since this means that an increase in a parameter for one trip is associated with a decrease in that same parameter for the second trip. The remainder of this section is dedicated to the presentation and discussion of day to day variation correlation results.

### 4.2.3 Day to Day Headway Variation

The first day to day variation considered is headway variation. This includes comparisons for a high speed arterial facility and a freeway facility. The correlation results for the high speed arterial facility are described next. The calculated correlation value for the two trips performed during week one was 0.3911 which indicated that there was some similarity between these two trips with respect to headway. Variability did exist, however, and was expected. Consider a routine drive
to work and the probability of following the exact same number of vehicles at exactly identical locations along the trip with identical headway values on any two days. It is very unlikely that two separate trips would have identical headway readings. A comparison of two trips performed in week two gave a correlation of 0.3852. This value was close to the value of that found for the week one pair. Day to day variation was, therefore, evident in this pair as well. The correlation found for the pair of trips taken across weeks was 0.5108. The increase in correlation value indicates that this pair of trips was more similar than either of the two already stated. This increase is not significant, however, due to the number of variables affecting headway readings of any given trip. There was variability between these two trips as seen in the following plot comparing the third trip from week one and the fifth trip from week two.

![Headway Correlation Graph](image)

**Figure 4-20 Headway Correlation (High Speed Arterial)**

Headway correlation values were also determined for driver 53 trip pairs. A correlation value of −0.1570 was found for the pair of trips performed in week one. As mentioned earlier, this negative value indicates a very poor relationship between
these two trips with respect to headway. The correlation of headway for the second week trip pair was found to be 0.5912. This value indicates that there was similarity between these two trips but it also suggests that there was still variability. Figure 4-21 below shows the week two headway data points. A correlation value of 0.2533 was calculated for the pair of trips that consisted of a trip performed in each week. Once again there is an indication of variability between trips with respect to headway.

![Figure 4-21 Headway Correlation (Freeway)](image)

Each of the above correlation values indicates that day to day variability existed on the high speed arterial facility and on the freeway facility. The maximum correlation value found was for a pair of freeway facility trips. There was more consistency for the driver 43 values, however, so one could potentially argue that there was less variability in headway on a high speed arterial compared to a freeway facility. Of course, there were many factors involved. A change in flow, for example, could cause a larger or smaller range of headway values observed. These correlation values, therefore, only serve as to reject the notion that two similar trips were identical. This notion is used for the remaining day to day variation determinations.
4.2.4 Day to Day Speed Variation

A comparison was also performed to determine if day to day speed variation occurred for both the high speed arterial and freeway facilities. The findings for driver 43 are discussed first followed by the driver 53 results.

The comparison of trips from week one produced a correlation value of 0.8732. This indicates a strong similarity between these two trips with respect to speed. Since the value calculated does not equal one, however, there was still some variability. On one hand, the averaging of data over 250 m bins may have smoothed out some speed fluctuations. This would have tended to produce a higher correlation value. On the other hand, there were locations where the speed value was zero (see Figure 4-8 above). This indicates that traffic signals may have been present on this facility. This would have increased the speed variability between trips resulting in a decreased correlation value. The two remaining speed correlation comparisons for the high speed arterial also indicated an increase in similarity compared to the headway correlation values. The comparison of trips from week two gave a correlation value of 0.6929 while the comparison of a trip performed in week one to a trip performed in week two produced a correlation value of 0.7728. Both indicate day to day variability in speed. Figure 4-22 is a plot of week one speed variability data.
The freeway facility (driver 53) results also show similarity of speed for all trip pair comparisons. The comparison performed for week one produced a correlation value of 0.7958. This indicates that speed variability existed between these two trips. As previously mentioned, grouping of data may have influenced the similarity between trips while daily flow fluctuations may have increased variability. Figure 4-14 and Figure 4-15 above both indicate that signals were present on this freeway facility. This could have created speed variability as described for driver 43. Figure 4-23 is a plot of the data points for the week one correlation calculation. The week two trips gave a correlation of 0.7783 and the comparison across weeks indicated a correlation of 0.7799. Both of these values are comparable to the result obtained for the week one data. Similar to the high speed arterial situation, each of these speed correlation values were greater than the correlation values determined for headway.
Each of the above trip pair comparisons indicate that day to day speed variability existed for both the high speed arterial and freeway facilities. The speed correlation values calculated for the trip pairs described above are each greater than the maximum headway correlation value determined in the previous section. It seems reasonable that speed would be more consistent between two similar trips than headway. For example, a driver may choose to drive at the posted speed limit. The driver could maintain this chosen speed for a range of headway values. Assuming that the driver chooses to drive at the posted speed limit the second day, the speed correlation value has the potential to be greater than the headway correlation value. Both headway correlation and speed correlation values suggested that day to day variability existed with respect to these two variables. The final day to day variation discussion is with respect to acceleration variation and follows in the next section.

4.2.5 Day to Day Acceleration Variation

The final day to day variation determination considered vehicle acceleration. Once again, driver 43 high speed arterial data and driver 53 freeway facility data were
analyzed. The week one pair comparison for driver 43 produced a correlation value of 0.6703. As described in the previous sections, this value indicates that variability does exist between these two trips. The pair of trips taken from week two gave a correlation value of –0.2006. The acceleration data plot for the week two comparison is shown below in Figure 4- 24. The negative correlation value determined for this trip pair indicates large variability between these two trips. The comparison of trips with one from each week produced a correlation value of 0.01201. Since this value is very close to zero there was very little relationship between the acceleration of the two trips. There is a large difference between the acceleration correlation values for the high speed arterial. Previously it was noted that traffic signals were likely present on this facility. This may explain the varying correlation values. If one day the driver reached a signalized intersection during the green phase while the next day they reached it at the red phase then the acceleration patterns for these two similar trips would be very different. The number of signals encountered could create a cumulative effect. It seems that the week one pair trips arrived at a given signalized intersection at approximately the same point of the cycle while the trips chosen for the week two comparison arrived during different phases.

![Figure 4- 24 Acceleration Correlation (High Speed Arterial)](image-url)
The freeway facility data produced more consistent acceleration correlation values than the high speed arterial facility. The week one trip comparison gave a correlation of 0.1441. This value is much closer to zero than to one and indicates day to day variation in acceleration. Figure 4-25 is a plot of the acceleration data for both week one trips. Both the comparison of the week two trips and the comparison of one trip from week one to one trip from week two indicate day to day acceleration variation. The correlation value for the week two data was calculated as 0.2136 while the comparison across weeks gave a correlation value of 0.4081. As previously indicated, traffic signals were used on this facility. Therefore, the discussion pertaining to the arrival at traffic signals applies here as well.

![Figure 4-25 Acceleration Correlation (Freeway)](image)

Each trip pair comparison performed for the determination of day to day acceleration variation indicated that variability existed with respect to acceleration. Also, it was found that the correlation between trips with respect to acceleration take on a large
range of values. This wide range of values was thought to be partly due to the presence of traffic signals on both facilities analyzed.

Overall, it was determined that day to day variations existed for headway, speed and acceleration for the high speed arterial and the freeway facility. The correlation values for speed were found to show the most similarity between trips while both the headway and acceleration data produced a range of correlation values.

This section has looked at the day to day variation of similar trips with respect to the facility traveled on. The next section considers differences in car following behavior based on the facility used as well as driving mode.

4.3 Comparison of Car Following Behavior

Car-following behavior comparisons are made in this section between ICC, CCC and manual driving. Two preliminary analyses are also included in this section. The first analysis was to determine the most probable speed, acceleration and headway for each driving mode for both road classes considered. The second determined the probability of using cruise control for each road class based on driving speed.

4.3.1 Mode Use Based Upon Speed, Acceleration and Headway

The purpose here was to determine the percent use distributions with respect to speed, acceleration and headway for each driving mode. This way, the most likely speed, acceleration and headway were determined given that a particular mode was in use. This analysis was performed for the data extracted for the high speed arterial and the freeway facility.

The trip data extracted for each facility were combined based upon driving mode. Therefore, all CCC data from week one trips and all ICC data from week two trips
were combined into one data set for CCC and another for ICC. Similarly, all manual driving mode data were combined. This meant combining manual data from both test weeks. Any data with range equal to zero were removed. As previously indicated, the range equal to zero values actually represent situations where there was no lead vehicle or the lead vehicle was too far away to determine the actual range. Including these points would impact the percentages determined for the distance headway graphs. In order to make a more direct comparison between the three driving modes percentages were determined over identical speed ranges. The minimum speed for each mode was determined and any data below the maximum of these minimum speed values were removed.

The following two charts show the relationship between speed and mode use. The percentages were calculated based upon five kilometer per hour speed bins. Figure 4-26 illustrates the results obtained for the high speed arterial facility followed by the freeway facility results in Figure 4-27.

![Figure 4-26 High Speed Arterial Speed Distributions](image-url)
The above figure implies that the most probable speed varied between the modes. The manual driving mode was used most in the 40km/h to 45 km/h speed range while both cruise control driving modes had their maximum percentages in the 75 km/h to 85 km/h range. The maximum percentage values varied between modes. The maximum for both manual and ICC driving occurred between 20 and 25 percent, while the maximum for CCC was between 45 and 50 percent. This indicates that the use of both ICC and manual driving modes were more spread out over the speed bins than CCC. This was not the case, however, for the freeway facility shown next.

![Figure 4-27 Freeway Speed Distributions](image)

**Figure 4- 27 Freeway Speed Distributions**

The maximum percentages observed for the freeway facility, shown above, occurred closer together than for the high speed arterial facility. In this case, the maximum percentages were higher than in the high speed arterial case but the range of speed values was lower.

Similar charts to the two shown above were created based upon acceleration bins. The bin size used for these charts was 0.05g. The high speed arterial chart indicates
more variability for the manual driving mode than for the two cruise control modes. This was also the case with the freeway facility, but to a lesser extent. For both facilities, the majority of acceleration values fell into the –0.05g to 0.05g interval. These two acceleration charts are shown next.

Figure 4-28 High Speed Arterial Acceleration Distributions

Figure 4-29 Freeway Acceleration Distributions
The final calculations determined the percentages for distance headway and time headway. The distance headway charts are shown first. The bin size for distance headway was 10 m. Unlike the previous charts, distributions for the high speed arterial were not similar in shape. The highest CCC percentage occurred at a higher headway bin than both the manual and ICC driving modes. The high speed arterial headway percentages are shown next followed by the percentages for the freeway facility.

![Figure 4-30 High Speed Arterial Distance Headway Distributions](image)
The freeway facility headway percentage chart shows more similarities between the modes than the high speed arterial chart. The maximum values for both CCC and manual occurred at the 28 m to 38 m headway bin. The maximum for the ICC driving mode occurred at the 48-58 m headway bin.

Comparisons were also made with respect to time headway. Time headway values for situations with no lead vehicle or for large vehicle separation were recorded as 50 second time headway values. The following two figures show the percentages associated with time headway for the high speed arterial facility. The first includes the 50 second time headway values while the second does not. Note that the ICC and manual driving modes were very similar with respect to their percentages. Time headway values of 1 to 3 seconds produced the maximum percentages for these two modes while the maximum percentage for the CCC mode occurred in the 3 to 4 second bin. The 50 second data affects the CCC curve the most since over 50 percent of the CCC values were measured at 50 seconds.
Figure 4-32 High Speed Arterial Time Headway Distances (With 50 second data)

Figure 4-33 High Speed Arterial Time Headway Distributions (Without 50 second data)
Time headway charts were also created for the freeway facility. Each driving mode seemed to be different although the inclusion of 50 second data made the ICC and manual driving modes’ distributions look more similar. The ICC peak occurred in the 1 to 2 second headway bin while in this case the manual mode peak occurred in the 0.5 to 1 second headway bin. The CCC, like the ICC mode, peaked at the 1 to 2 second bin. These two charts are shown next.

Figure 4-34 Freeway Time Headway Distributions (with 50 second data)
Facility = Freeway

Figure 4-35 Freeway Time Headway Distributions (without 50 second data)

The most likely speeds, acceleration and headway values have been determined for both a high speed arterial facility and a freeway facility with respect to driving mode. The high speed arterial showed more of a difference between the modes than the freeway regarding speed. The most probable speed for manual driving on the arterial was found to be lower than both cruise control modes whereas on the freeway the maximum percentages for each mode were found to lie within a 10 km/h interval. Acceleration, unlike speed, was found to be very similar for both facilities. The highest percentages were found for the \(-0.05g\) to \(0.05g\) interval. The main difference was with the manual driving mode where on the high speed arterial the range of accelerations observed were greater than on the freeway. The final comparisons were made based upon distance and time headway. As described, the distance headway percentages found for the high speed arterial showed peak values but very little similarity between driving mode distributions. The figure created for the freeway facility showed mode distributions that were more similar than that for the high speed
arterial. The time headway charts for both the high speed arterial and freeway indicated similarities between ICC and manual driving modes.

4.3.2 Probability of Cruise Control Use

In the previous section if a particular driving mode was used, then the most likely speed, acceleration and headway that the vehicle would travel at could be determined. In this section, the probability of cruise control use based upon driving speed is determined. Facility data were once again separated by mode, including the separation between week one and week two manual data. Probabilities of cruise control use were determined for 5 km/h speed bins. Included were the data points where range equaled zero. These points were included since the number of observations where range equaled zero were not the same for all modes and thus would affect the calculated probabilities if removed. Charts were again created for each facility under consideration: high speed arterial and freeway. The probability of using cruise control on the high speed arterial facility is shown below in Figure 4-36.

![Figure 4-36 Probability of Using Cruise Control on the High Speed Arterial Facility](image-url)
Several observations can be made with respect to cruise control use on a high speed arterial from the above figure. At speeds up to 75 km/h the probability of using ICC exceeded the probability of using CCC. From 75 km/h to 85 km/h, however, the probability of CCC use exceeded the probability of using ICC. The maximum probability of using either mode was approximately 0.06. The cumulative percentages of using either cruise control mode indicated a preference for ICC use on the high speed arterial. The total cumulative probability of using ICC was between 0.25 and 0.30 while the CCC total cumulative probability was just above 0.15. The cumulative probability curves for CCC and ICC are shown in Figure 4-37 below.

Figure 4-37 Cumulative Probability of using Cruise Control on High Speed Arterial Facility

As indicated above, probability distributions for ICC and CCC use on a freeway facility were also calculated. Similar to the high speed arterial, at lower speeds the use of ICC exceeded the use of CCC. The probability of using CCC did not exceed the use of ICC at any speed on this facility. The maximum probability of using CCC on this freeway facility was calculated as approximately equal to 0.1, which was
higher than the maximum found for the high speed arterial facility. The maximum probability for ICC on the freeway facility was greater than 0.20 while the high speed arterial use maximum was approximately 0.06. It is no surprise, therefore, that the cumulative probability plot shows a large difference between ICC and CCC use. The total cumulative probability of CCC was close to 0.2 while the cumulative probability for ICC was approximately 0.5. The probability and the cumulative probability of using cruise control on the freeway facility are shown below.

Figure 4-38 Probability of using Cruise Control on the Freeway Facility
As indicated in the discussion above, the probability of using either cruise control mode was higher on the freeway facility than on the high speed arterial. The probability of ICC use was greater than that of CCC use for speeds less than 75 km/h on the high speed arterial and for all speeds on the freeway facility. ICC has seemed to increase the usage of cruise control on both of the facilities analyzed.

4.3.3 Aggregated Speed-Headway Relationships

The purpose of this section is to compare manual and cruise control speed headway relationships. This was accomplished by creating plots of headway versus speed based on mode including 95% confidence limits. As in the previous sections, the analysis was performed for both the high speed arterial and freeway data.

The mean headway and mean speed were calculated for 5 km/h speed bins. Plots are based upon these calculated data. The calculation of the confidence intervals
assumed normality of the data within each one of the speed bins. This was checked using manual driving mode data from three speed bins. Frequency distributions were plotted over 10 m headway bins and compared to a normal distribution based on random number generation. The three frequency plots obtained for the high speed arterial data are shown in Figure 4-40, Figure 4-41 and Figure 4-42.

![Figure 4-40 High Speed Arterial Normality Check 1](image)

![Figure 4-41 High Speed Arterial Normality Check 2](image)
The frequency distribution plots for both the 30 km/h to 35 km/h and the 55 km/h to 60 km/h speed bins visually support the normality assumption. The frequency plot for the 80 km/h to 85 km/h speed bin does not follow the normal curve as well as the other two but is considered sufficient to continue with the normality assumption. The plots created for the freeway facility were again based upon 10 m headway bins and produced for three speed bins.
Figure 4-44 Freeway Normality Check 2

The frequency distribution for the 55 km/h to 60 km/h speed bin definitely suggests normality. The distribution for the 80 km/h to 85 km/h, however, indicates a bit of skewing for the manual headway data. It is assumed that the normality assumption is not violated. The frequency distribution for the 100 km/h to 105 km/h speed bin is also assumed to have a normal distribution even though there is evidence of slightly skewed data.
As indicated, the confidence intervals were created based upon the assumption of normal data. Each cruise control mode was plotted against the manual mode. The charts produced for the high speed arterial are shown below.

![Chart showing Conventional Cruise Control and Manual Mean Headway versus Mean Speed (High Speed Arterial)](image)

Facility = High Speed Arterial

**Figure 4-46 Conventional Cruise Control and Manual Mean Headway versus Mean Speed (High Speed Arterial)**
The speed headway relationship shown for CCC does not match the trend of the relationship for the manual mode of driving. There are, however, portions where the 95% CCC confidence interval included the manual mean headway. The number of observations used to calculate the confidence interval may be of some concern. Note from Figure 4-48 above that the number of observations for CCC for several of the
speed bins was quite low. This produced a larger confidence interval suggesting that the mean headway could be equal to the manual headway.

Figure 4-47 above shows that the ICC mean headway curve follows the manual mean curve much more closely than the CCC curve. There are, however, only a couple of points where the 95% confidence envelope captured the manual mean curve. The number of observations for the ICC mode was greater than CCC so the confidence envelope was smaller and it was more difficult to suggest that the means were in fact equal.

The figures suggest that the use of ICC was more similar to the manual mode of driving than the CCC driving mode. The trends seen in the mean headway plots above indicate that ICC followed a distribution similar to the manual mode. Since the manual curve did not lie within the 95% confidence interval of the ICC, it can not be suggested that they were equal (at the 5% error level).

The mean headway versus speed relationship discussion continues with comparisons for the freeway facility. Figure 4-49 below shows the manual mean headway speed relationship for the freeway facility as well as the CCC mean headway speed curve with 95% confidence intervals. CCC was used over only seven speed bins but the relationship matches the manual relationship over three of these intervals. As discussed for the high speed arterial, a larger number of observations should produce a more accurate result. It could be argued that the accuracy of the last two CCC bins is in reality low due to the low number of observations. Figure 4-51 shows the number of observations in each speed bin.
Figure 4-49 Conventional Cruise Control and Manual Mean Headway versus Mean Speed (Freeway)

The ICC mean headway-speed relationship follows the manual trend but not over every speed range. From approximately 50 km/h to 85 km/h the two relationships are very similar. At speeds greater than 95 km/h, however, the mean headway for ICC was shown to be greater than that for manual driving. The largest difference occurred for the highest speed bin. The large difference between curves for the highest speed bin may be accounted for due to the fact that the number of observations for the ICC mode was quite small in this speed bin.
Comparisons between cruise control and manual driving mean headway speed relationships have been made above. Each cruise control curve showed similarities to and differences from the manual curve. The CCC mode was very different from the manual mode for the high speed arterial but included the manual mean over several speed bins with 95% confidence for the freeway facility. The ICC trend followed the
mean manual distribution over every speed bin it was used in for the high speed arterial. There were, however, only a couple of locations where the manual mean was included in the ICC mean confidence interval. The manual mean was found to be included over several speed intervals for the freeway facility data. At higher freeway speeds, the ICC mean headway values were greater than those determined for manual driving. Overall, ICC driving was found to be more comparable to manual driving than to CCC driving.

In this section it was determined how the two cruise control driving mode relationships compared to the manual mode for both high speed arterial and freeway data. Further detail is desired on actual speed headway relationships. This is addressed in the following section.

4.3.4 Speed-Headway Relationships

The purpose of this section is to illustrate the speed relationships to headway, density and flow for both the high speed arterial and freeway facility. Similar to the previous sections of this chapter, the data was separated based on mode. Additional filters were used to restrict data to near steady-state conditions. A range rate envelope of –1 m/s to +1 m/s was used in addition to an acceleration limit of magnitude 0.01g. All data points where range was equal to zero were removed as well.

Speed-Flow-Density data were plotted and a single regime model was used to fit relationships to the data. Specifically, each relationship was determined considering speed, flow and density as dependent variables. The magnitudes of error were minimized in these three dimensions. For further detail regarding the fitting process, refer to Van Aerde and Rakha (1994).

Since the goal of the chapter is to observe car following relationships, the speed headway curves created for each mode are described in detail while the speed-flow
and speed-density charts are presented for completeness. The speed headway curves for CCC and ICC are shown below.

Figure 4-52 Conventional Cruise Control Speed-Headway Relationship (High Speed Arterial)

Figure 4-53 Intelligent Cruise Control Speed-Headway Relationship (High Speed Arterial)
The figures representing the speed headway relationships for both cruise control modes indicate that the set speed was approximately 80 km/h for both modes. As shown in Figure 4-26 earlier this chapter, the maximum use for both modes was in the 75 km/h to 85 km/h range. Therefore, the fitted curves are in agreement with this observation. The manual plot has a slightly different shape than the two cruise control plots. Most data, as expected, was observed at lower speeds. The speed headway plot for the manual data is shown below.

![Speed Headway Relationship](image)

**Figure 4-54 Manual Speed-Headway Relationship (High Speed Arterial)**

The speed headway curves for each mode were combined into a single plot for comparison purposes. Figure 4-55 is the combined plot for the high speed arterial facility.
Several observations regarding speed headway relationships can be made from the above graph. The two cruise control curves are very similar. For the speed range of approximately 60 km/h to 80 km/h, the headway associated with ICC use was greater than that observed for the CCC driving mode. Theoretically, the ICC speed headway relationship is comprised of two line segments. The segment representing speeds below the selected speed would have a slope equal to the inverse time headway selected by the driver while the other segment at the selected speed would have a slope of zero. Since the driver has more than once choice for time headway selection and a large number of choices for selected driving speed, the actual slopes would be a combination of each chosen parameter.

For speeds less than 80 km/h, the manual curve lies below both cruise control curves. Thus the headway chosen for manual driving was larger than that for either cruise control mode at these speeds. At speeds less than 20 km/h the chart indicates that the headway for manual driving was less than that for cruise control driving modes. Of
course, this is a hypothetical situation since cruise control can not be used at these speeds.

Similar to the process above, plots were created for speed flow and speed density data. The plots created for each mode are included in Appendix (G). The combination of the mode plots for these two relationships are shown below.

![High Speed Arterial Speed-Density Relationships](image)

**Figure 4-56 High Speed Arterial Speed-Density Relationships**

Since density and headway are inversely related, it is no surprise that the speed-density relationship for both cruise control modes is similar. The cruise control data covers only higher speeds which explains why the curve does not capture a tail portion as in manual case. Similarly, the manual data is focused on lower speeds. This results in the speed-flow relationship seen in the figure below.
Since flow is based upon speed and density, it was expected that the two cruise control modes have similar speed-flow curves.

As in the previous sections of this chapter, the data analysis was performed for both the high speed arterial and the freeway facility. Speed-flow-density data was plotted for each mode. Problems with the data were observed, however, and are now discussed with the aid of the speed-flow plot for the manual data shown below.
As seen in the above figure, the maximum flows obtained for this facility are on the order of 7000 veh/hr. The combination of high speed coupled with small range produced these large flow values. For example, points in the database were observed such that the speed was 96 km/h for a 23 m headway. In other words, a problem has occurred with the data collection process for at least one of the trips performed on the freeway facility by driver 53. Therefore, any comparison between modes (based on range) with respect to the freeway facility are invalid. The individual and combined mode charts are included in Appendix (G).

Although it was determined through this speed headway analysis that problems exist with the database for the freeway facility data, conclusions can be made with respect to speed headway relationships for high speed arterial driving. First of all, the two cruise control speed headway curves are very similar. The main difference occurs in the 60 km/h to 80 km/h speed range where ICC headway values are greater than CCC headway values. Secondly, the manual speed headway relationship indicates larger headway values than either cruise control mode at speeds less than 80 km/h.
4.4 Conclusions

Based on the microscopic like trip analysis, the following conclusions are drawn:

1. Day to day headway variability existed for the high speed arterial facility.
2. Day to day acceleration variability existed for the high speed arterial facility and the freeway facility.
3. Day to day speed variability existed for the high speed arterial facility and the freeway facility. Speed correlation values indicated more similarity between trips and were more consistent than either headway or acceleration correlation values.
4. Most probable manual driving speed on the high speed arterial was lower than the most probable ICC or CCC driving speeds.
5. The most probable freeway driving speeds for manual, ICC and CCC were within a 10 km/h interval.
6. The most likely acceleration rates on either the high speed arterial or freeway facility were within –0.05g to 0.05g for manual, ICC or CCC driving modes. The range of manual driving mode acceleration values observed for the high speed arterial were greater than the freeway values.
7. Cruise control (ICC or CCC) was used more on the freeway facility than on the high speed arterial.
8. ICC was used more than CCC at speeds less than 75 km/h on the high speed arterial and for all speeds on the freeway facility.
9. The ICC speed-headway curve was similar (not identical) to the CCC speed-headway curve created from high speed arterial data. The mean headway-speed charts, however, indicated that ICC was more similar to manual driving than the CCC mode.
10. Manual driving resulted in larger headway values than either CCC or ICC at speeds less than 80 km/h (high speed arterial).